Topology Control from Bottom to Top

M. Steenstrup
Stow Research L.L.C.
Clemson University
steenie@rcn.com

This work was funded in part by DARPA and by ONR MURI.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 DEC 2007	**N/A**	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Cross-Layer Issues In The Design Of Tactical Mobile Ad HOC Wireless Networks: Topology Control from Bottom to Top	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Clemson University**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**55**	

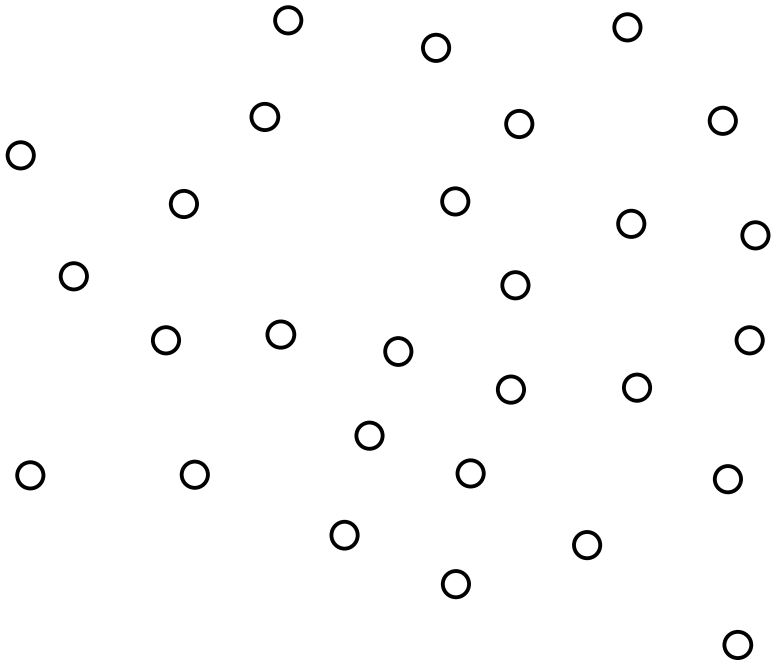
Cross-Layer Design

Cognizance of behavior of other control functions:
- fosters synergistic interaction
- reduces redundant functionality

Exchange of information between control functions:
- directives as well as state information
- level of abstraction may affect accuracy of control

Integrated design of multiple control functions:
- tight coupling for optimization
- specific combinations intended for use together

Mobile Wireless Network



Communications

Conditions:

- heterogeneous, mobile wireless devices
- operating in time-varying, unpredictable, and potentially hostile environment

Objective:

- must be consistent with service needs of traffic, capabilities of devices, and policies for resource use

Topology Control

Network topology:

time-dependent directed multigraph representing devices (nodes) and their ability to communicate directly with each other (links with different properties)

Goal:

determine which links between node pairs should be made available for transporting traffic from sources to destinations

Approaches:

- complete or partial view of network state
- global optimization for slowly-varying network conditions
- local optimization and heuristics for dynamic network conditions
- centralized, decentralized, distributed

History

Wireline networks:

- network design problem
- ordering of additional capacity based on predictions of load
- dial-up links for temporary replacement of lost connectivity and for additional capacity under heavy load

Wireless networks:

- minimize (maximum, total, average) transmit power for link closure while maintaining k-connectivity of network graph, $k \geq 1$
- use of node mobility to enable communication between nodes
- quality of service and interference considered secondary

Topology Control Functions

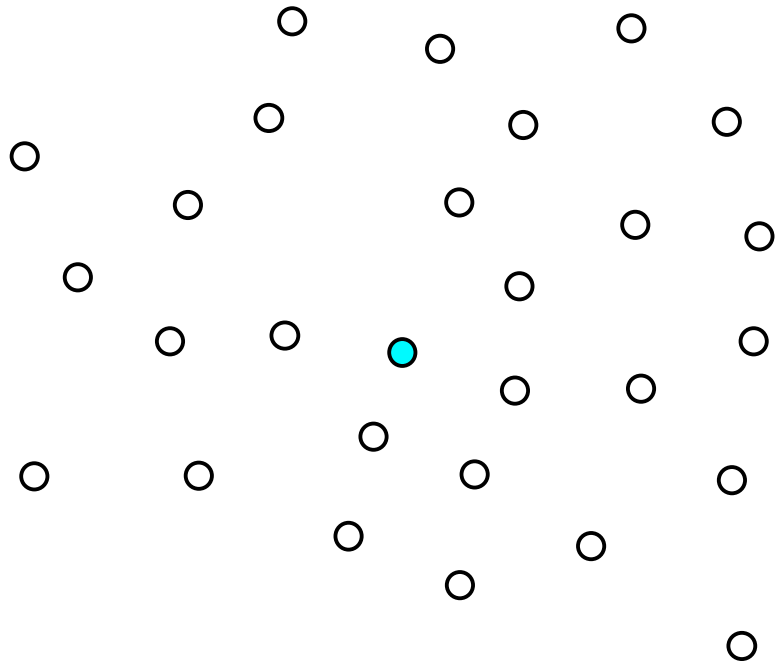
Node advertisement:
node announces presence and parameters for communication

Neighbor discovery:
node determines which nodes are within its transmission and reception ranges

Graph formation:
nodes negotiate and select persistent links for routing according to desired network properties and ephemeral links for specific sessions according to service needs

Graph maintenance:
nodes adjust graph according to perceived changes in channel conditions and mission directives

Single Node's Perspective



Topology Control Functions

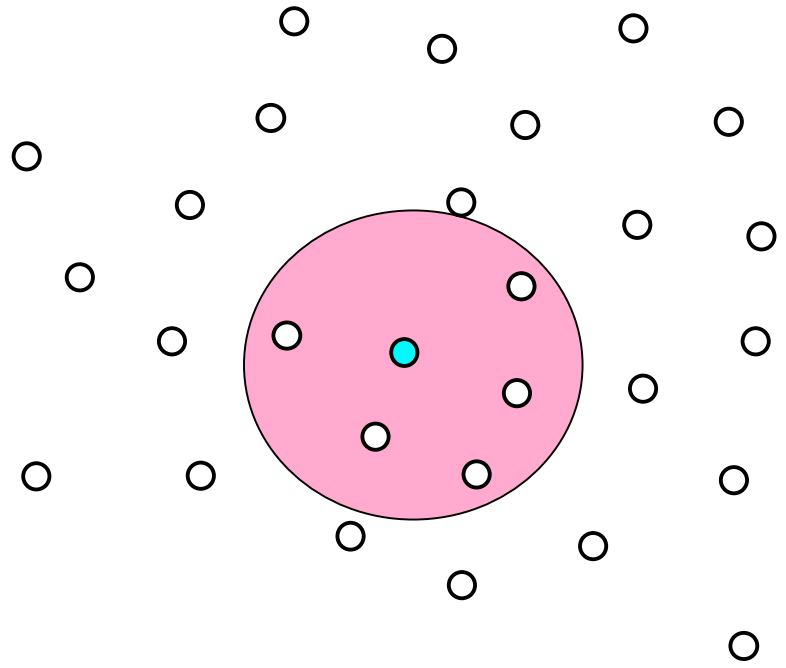
Advertisement:
node announces presence and parameters for communication

Neighbor discovery:
node determines which nodes are within its transmission and reception ranges

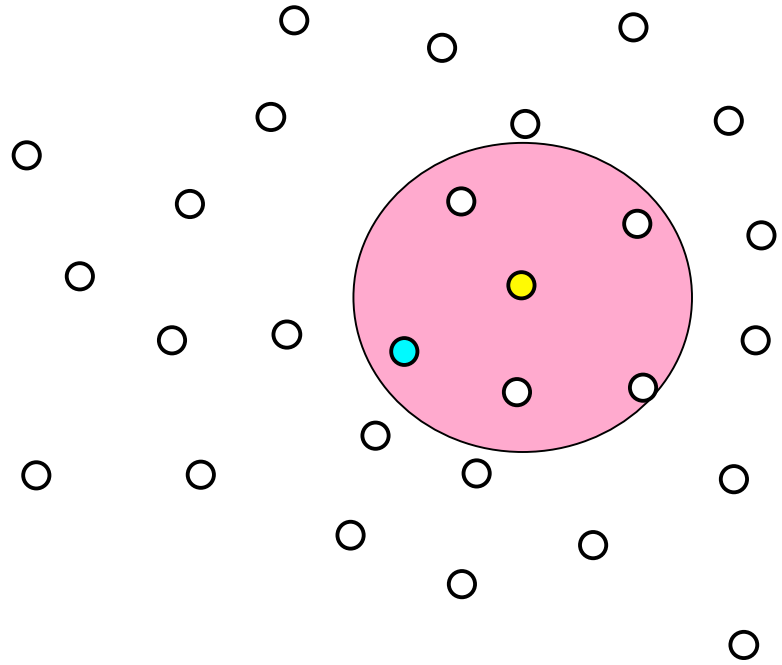
Graph formation:
nodes negotiate and select persistent links for routing according to desired network properties and ephemeral links for specific sessions according to service needs

Graph maintenance:
nodes adjust graph according to perceived changes in channel conditions and mission directives

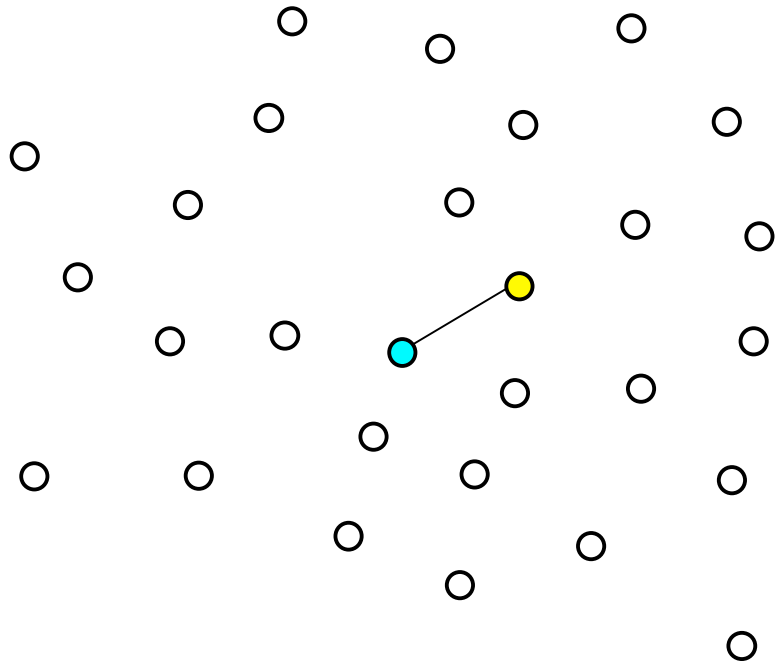
Low-Power Transmission Range



Low-Power Transmission Range



Achievable Low-Power Link



Topology Control Functions

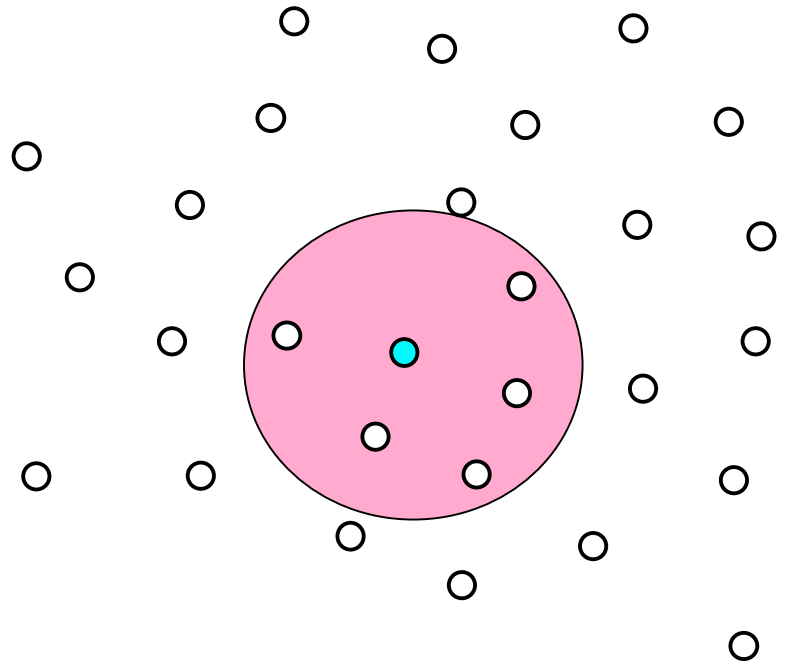
Advertisement:
node announces presence and parameters for communication

Neighbor discovery:
node determines which nodes are within its transmission and reception ranges

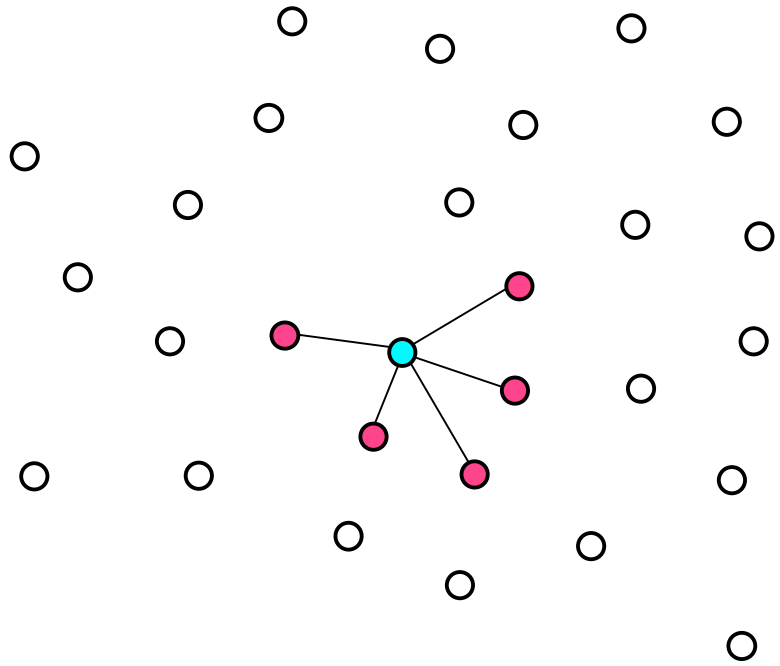
Graph formation:
nodes negotiate and select persistent links for routing according to desired network properties and ephemeral links for specific sessions according to service needs

Graph maintenance:
nodes adjust graph according to perceived changes in channel conditions and mission directives

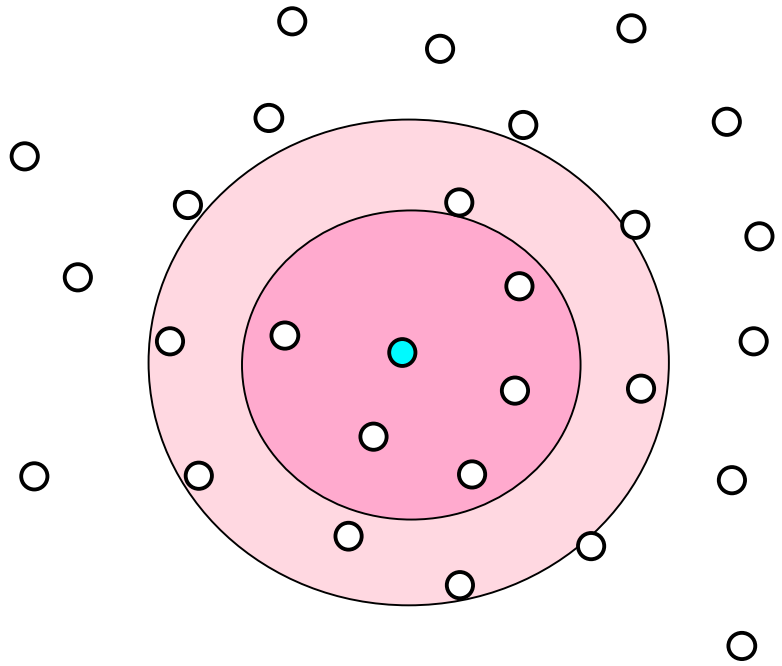
Low-Power Transmission Range



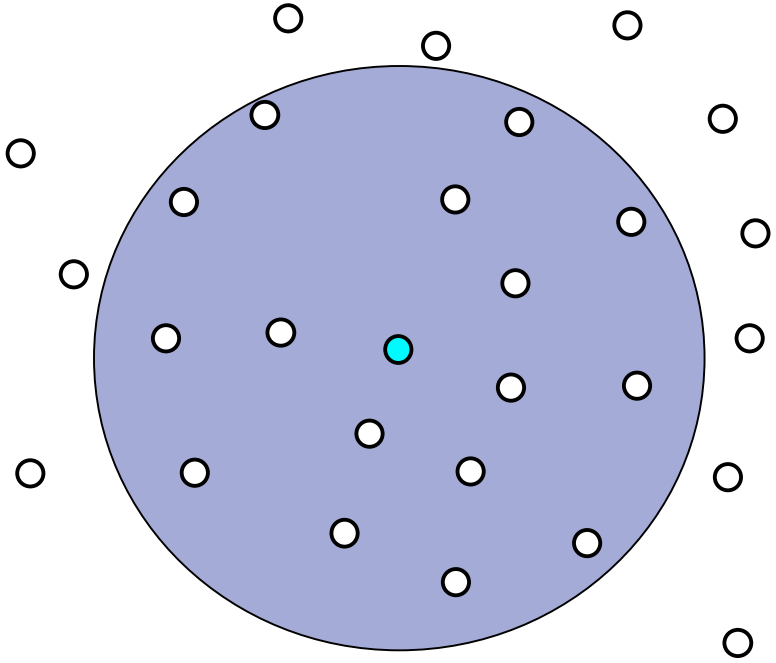
Achievable Links at Low Power



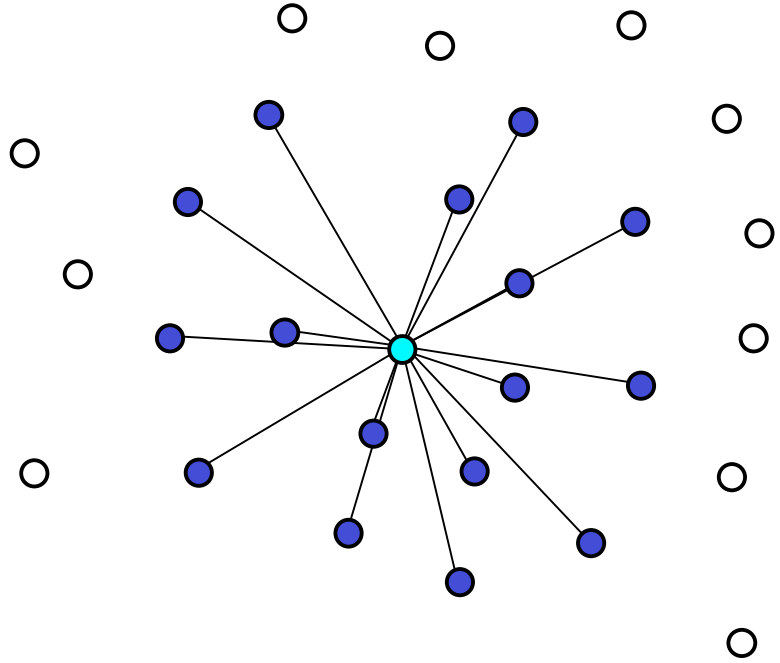
Low-Power Interference Range



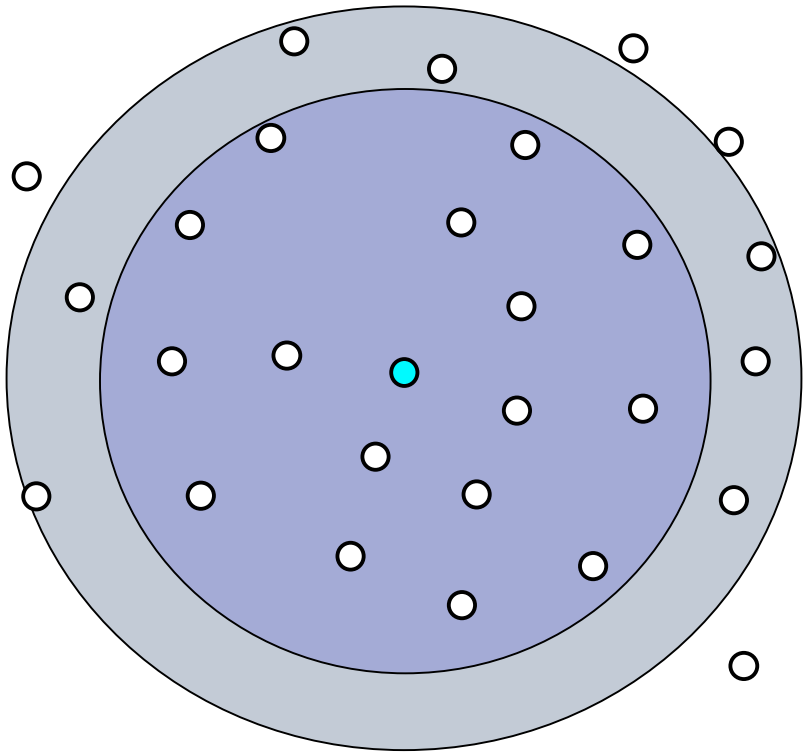
High-Power Transmission Range



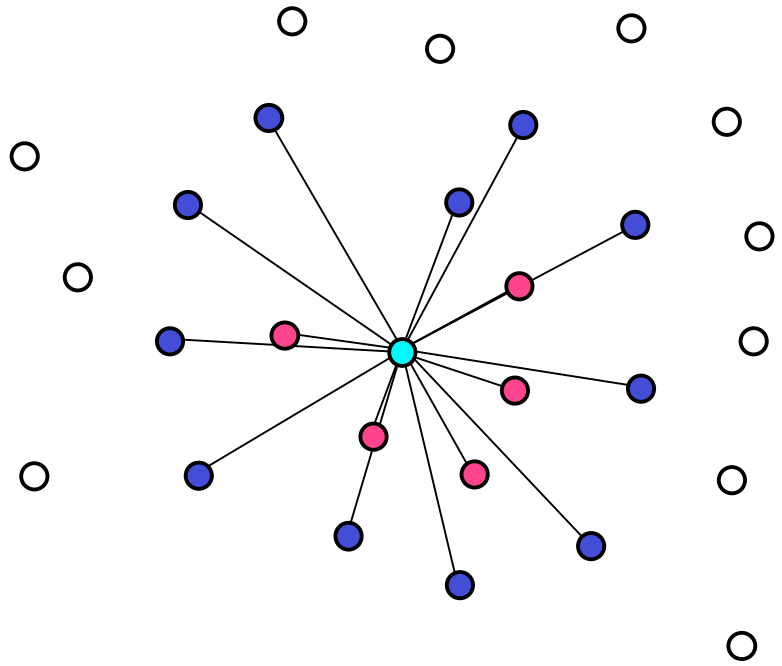
Achievable Links at High Power



High-Power Interference Range



All Achievable Links



Topology Control Functions

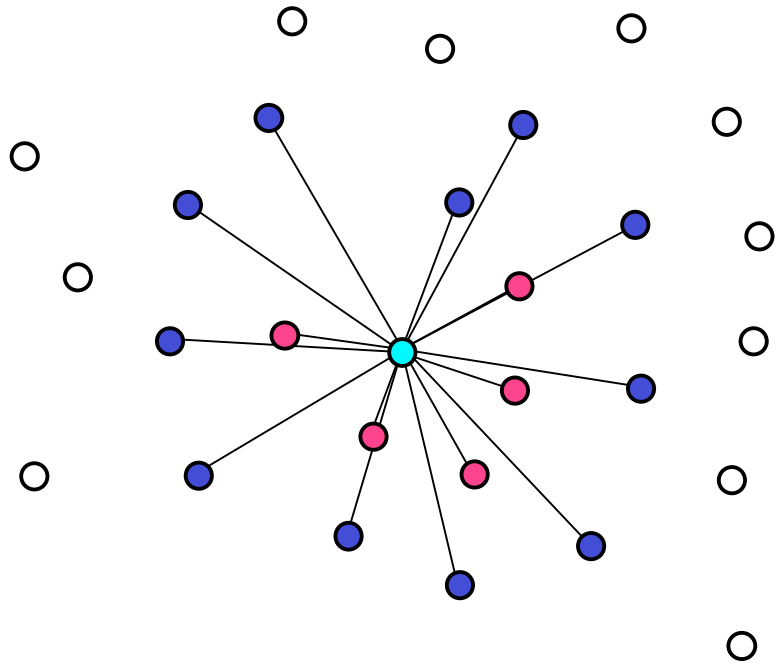
Advertisement:
node announces presence and parameters for communication

Neighbor discovery:
node determines which nodes are within its transmission and reception ranges

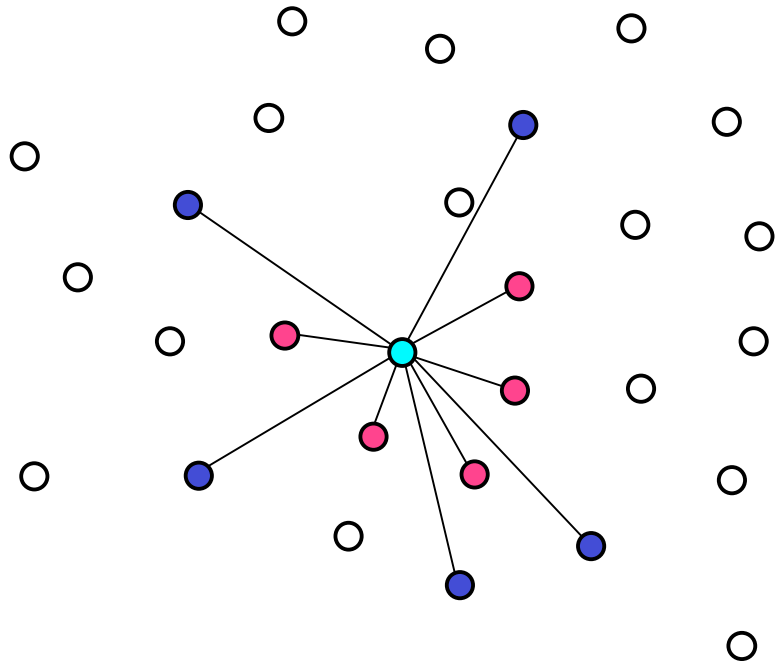
Graph formation:
nodes negotiate and select persistent links for routing according to desired network properties and ephemeral links for specific sessions according to service needs

Graph maintenance:
nodes adjust graph according to perceived changes in channel conditions and mission directives

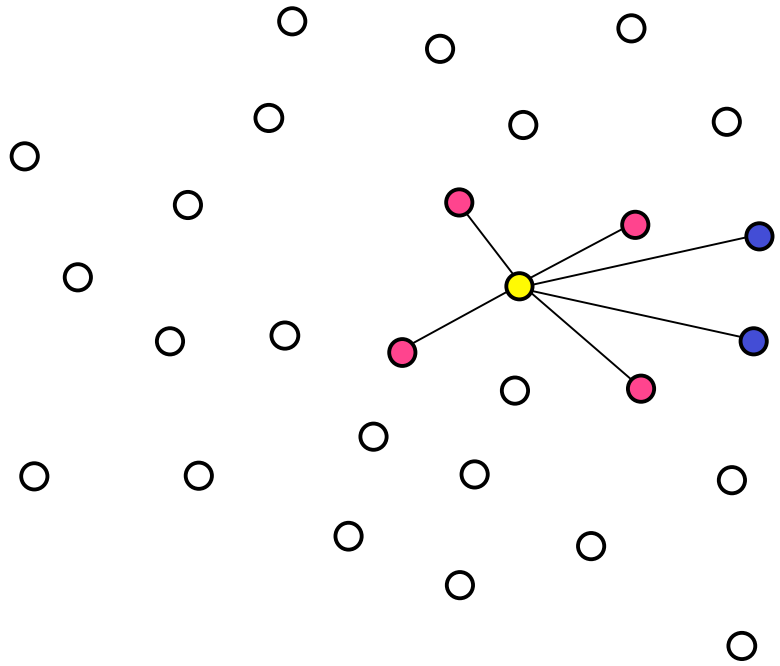
All Achievable Links



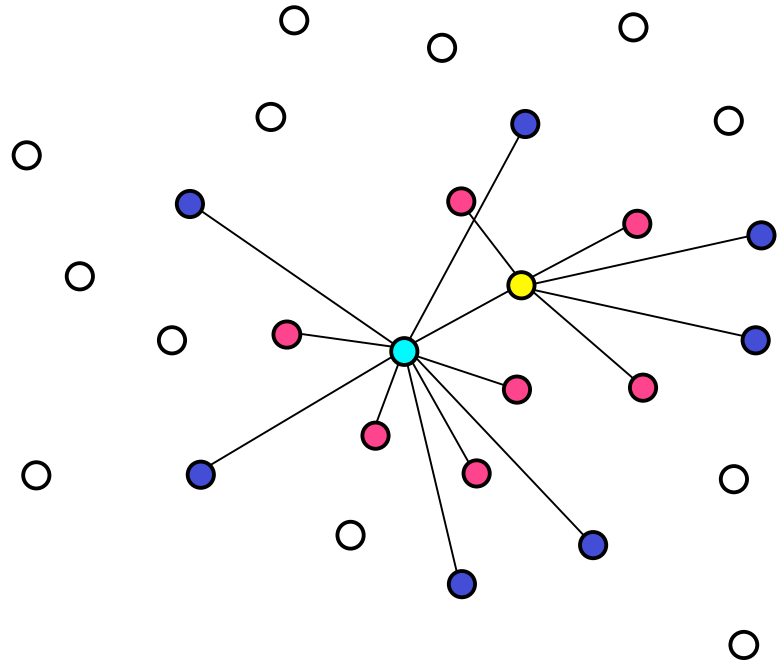
Selected Links



Selected Links



Partial View of Network Topology



Topology Control Functions

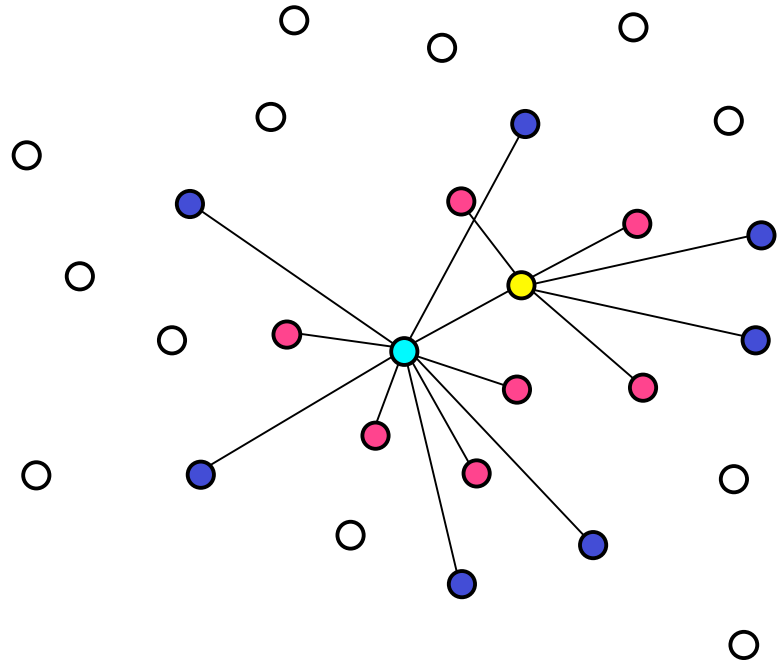
Advertisement:
node announces presence and parameters for communication

Neighbor discovery:
node determines which nodes are within its transmission and reception ranges

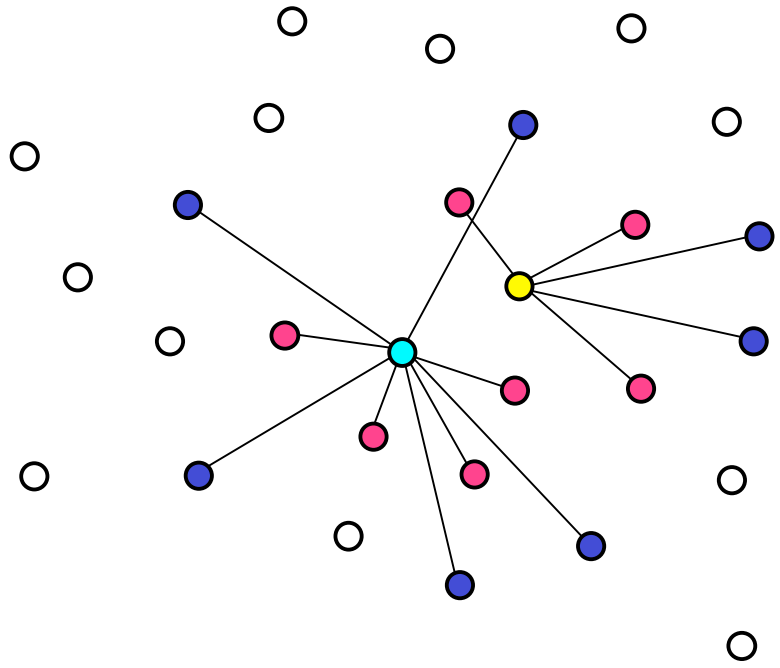
Graph formation:
nodes negotiate and select persistent links for routing according to desired network properties and ephemeral links for specific sessions according to service needs

Graph maintenance:
nodes adjust graph according to perceived changes in channel conditions and mission directives

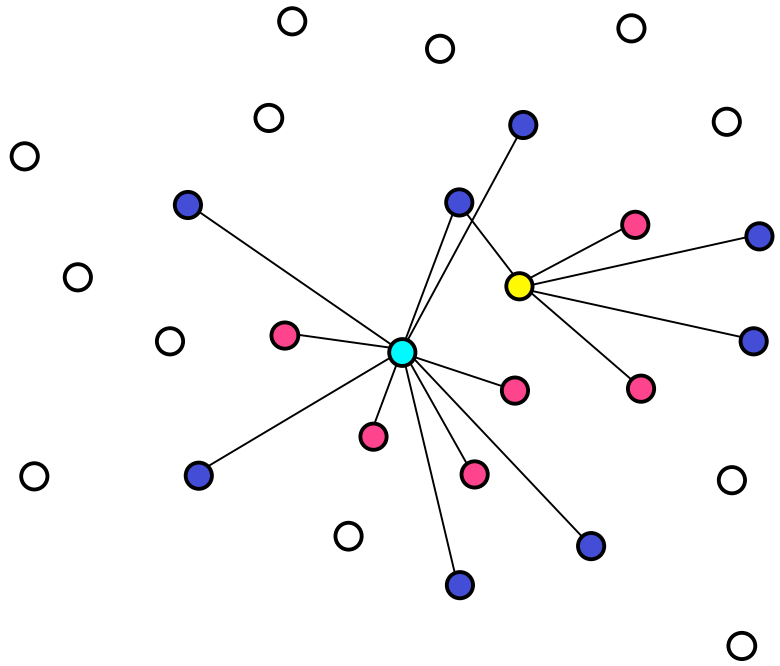
Partial View of Network Topology



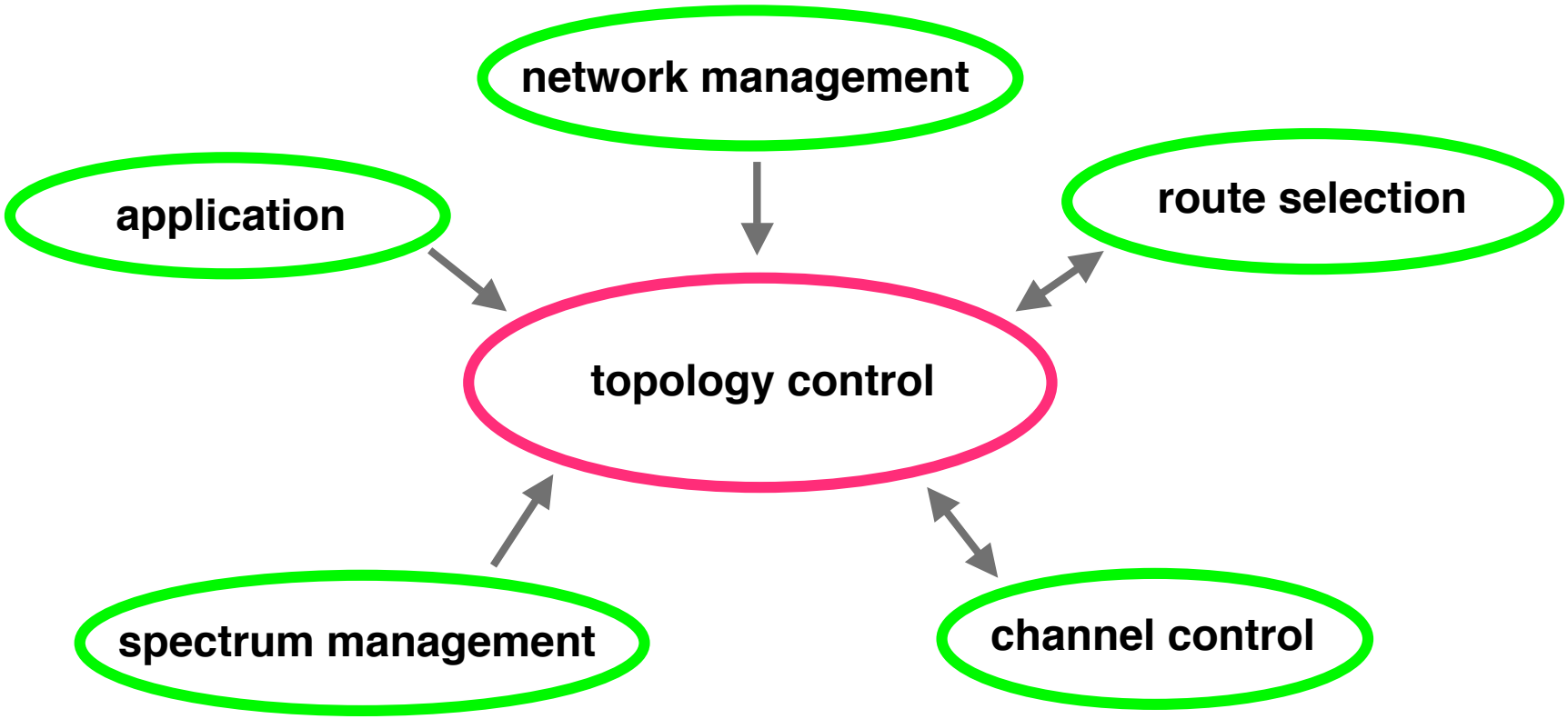
Partitioned Topology



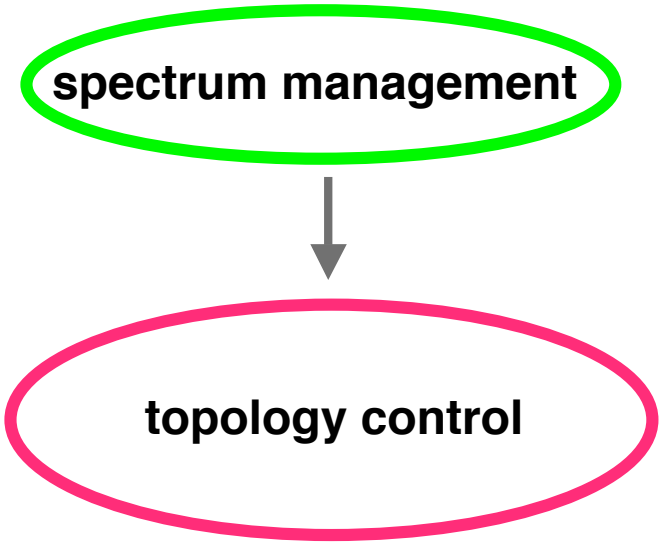
Reconnected Topology



Explicit Interactions



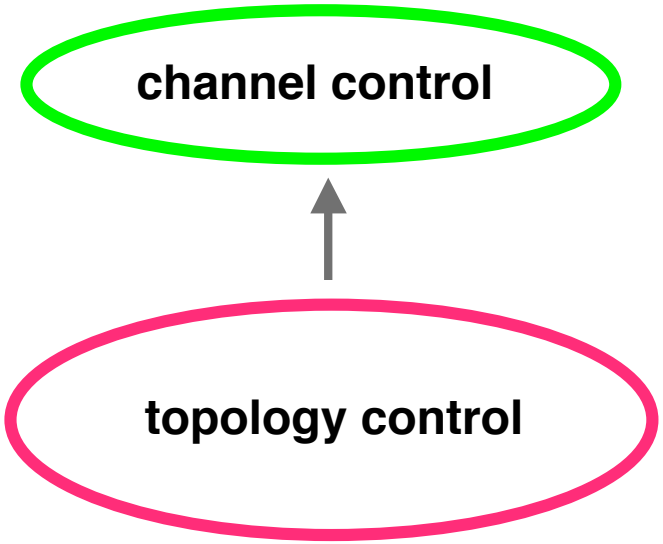
Available Spectrum



Spectrum opportunities:

- frequency bands
- tolerated interference
- expected lifetime

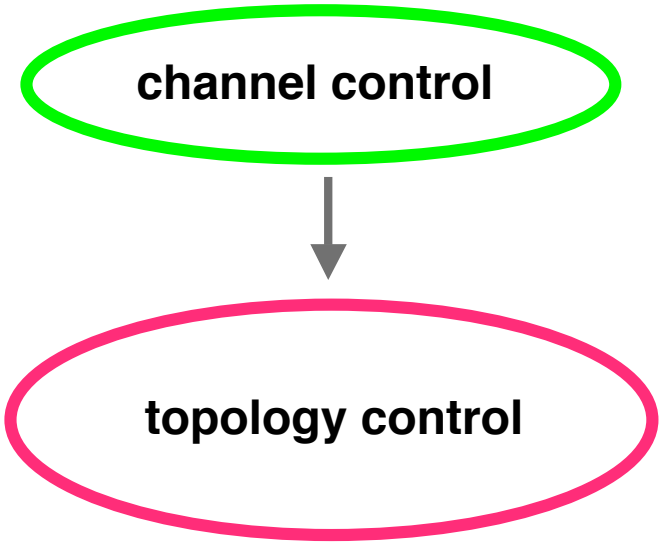
Probing and Scanning



Transceiver and antenna parameters:

- frequency
- transmit power
- modulation
- error-control coding
- beam width
- beam direction

Perceived Channel



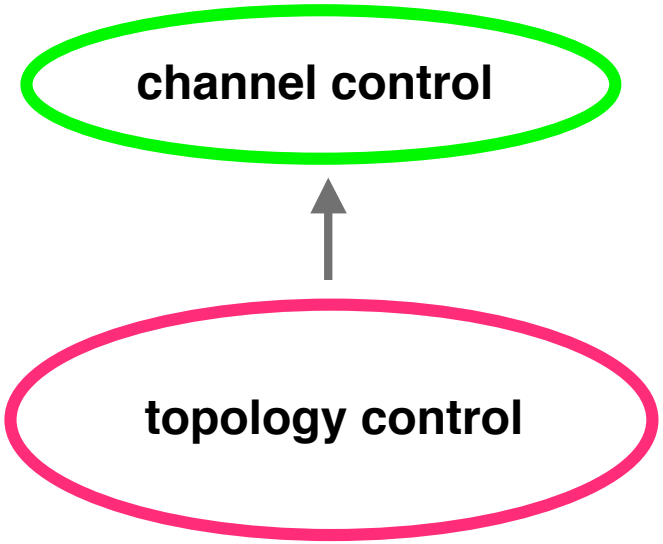
Channel properties:

- received signal strength
- signal-to-noise-plus-interference ratio
- bit error rate

Transceiver and antenna parameters:

- frequency
- transmit power
- modulation
- error-control coding
- beam width
- beam direction

Desired Channel



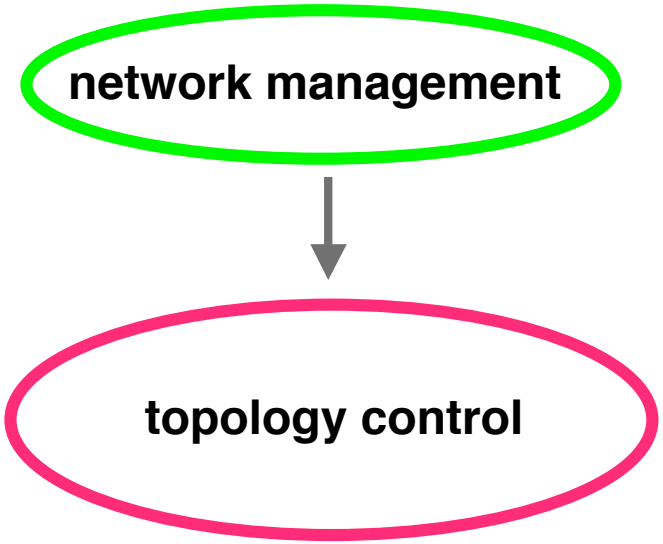
Channel properties:

- received signal strength
- signal-to-noise-plus interference ratio
- bit error rate

Limits on cost:

- transmit power
- energy for transmission
- air time for transmission

Admissible Links

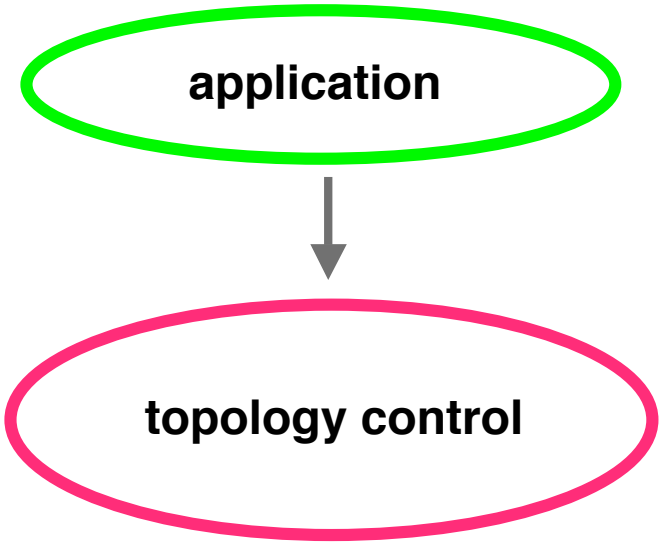


Desired graph properties:
- degree
- diameter
- connectivity
- cut capacity

Desired network properties:
- interference
- energy consumption
- detection probability

Positional information:
- node trajectories
- probable location of detectors

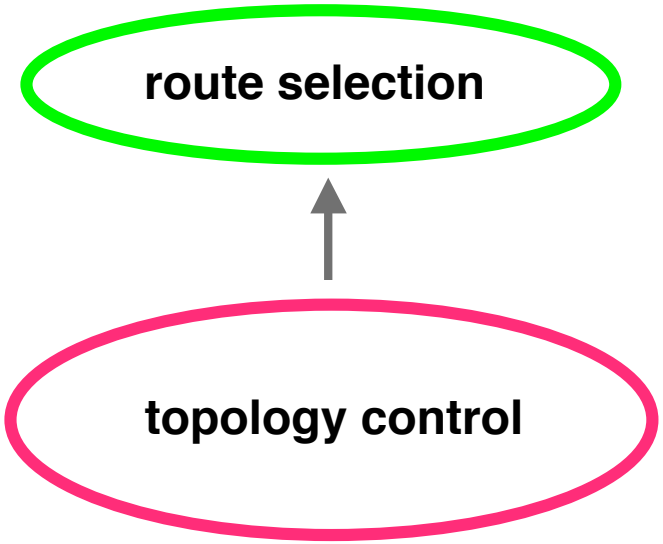
Ephemeral Links



Quality of service:
- delay
- throughput
- loss

Session properties:
- source and destinations
- priority
- expected lifetime

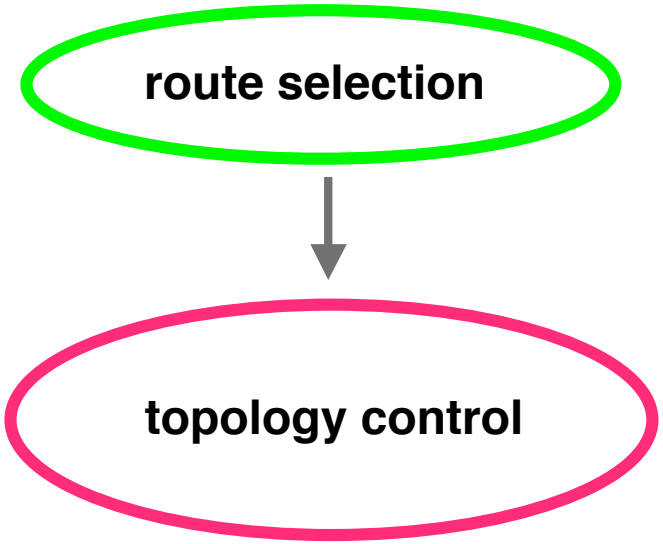
Network Topology



Links:

- performance metrics
- costs
- expected lifetime

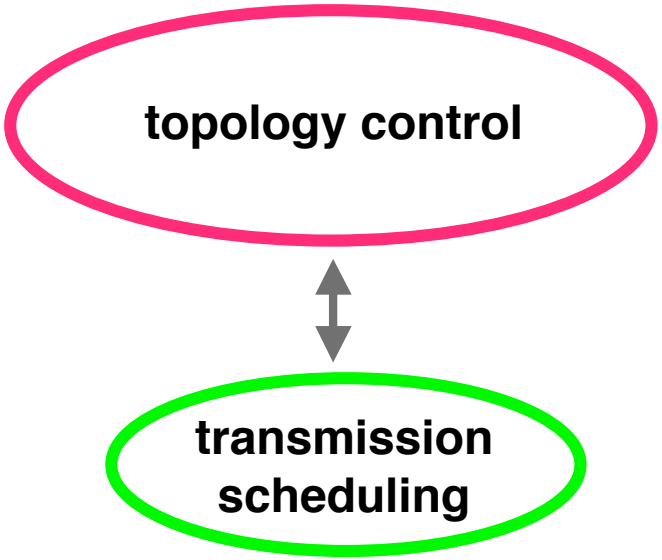
Routes for Updating Topology



Routes:

sequence of nodes
performance metrics
costs

Implicit Interactions



Efficient use of channel versus rich connectivity:

- interference
- route length

Example: Link Activation

Assumptions:
- stationary network
- traffic flows known
- achievable links known
- slotted medium access

Objective:
- minimize total delay to send all traffic

Approach:
- flow scheduling: for each time slot determine which links to activate for which traffic flows
- combined topology control, route selection, and slot scheduling

Examples: Ephemeral Links

Direct link versus multihop path:
- performance benefits
- costs

High-priority application requests:
- low delay
- high throughput
- low packet loss

Network management desires:
- low interference
- low probability of detection

Example 1

Assumptions:

- omnidirectional transmissions
- transmit power adjustable in discrete levels
- no malicious detectors
- objective: minimize potential interference

Cost:

$\sum_{i=1,h} \pi r_i^2 \rho_i (\tau_i/\tau_{min})$

h: number of hops from source to destination

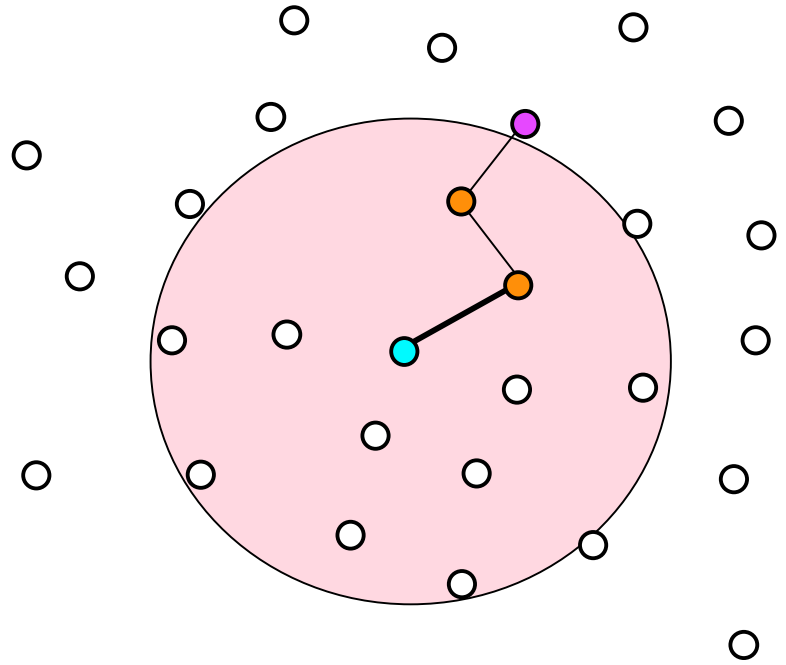
r_i: omnidirectional interference range for hop i

ρ_i: expected density of nodes around hop i

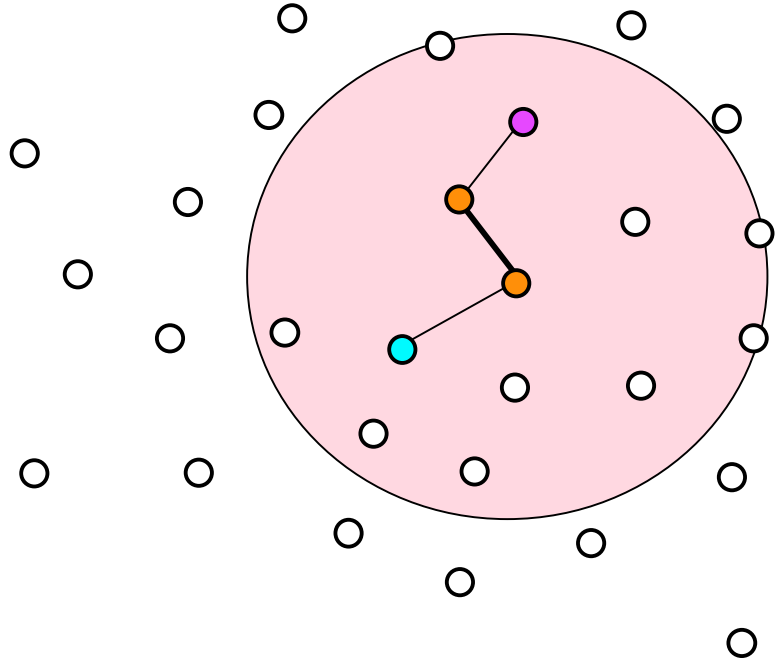
τ_i: expected air time for packet over hop i

τ_{min}: minimum expected air time over all hops considered

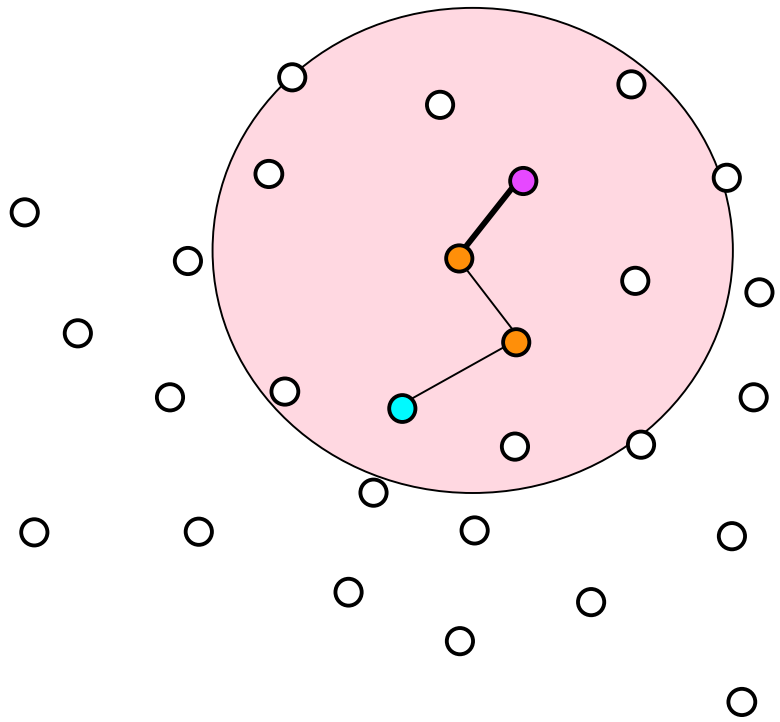
Low-Power Transmission



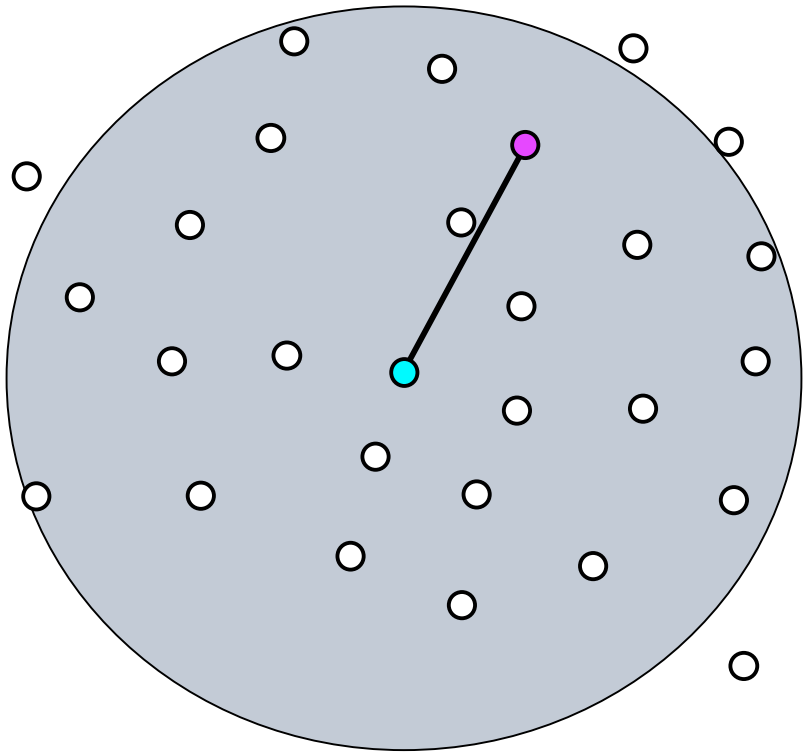
Low-Power Transmission



Low-Power Transmission



High-Power Transmission



Example 2

Assumptions:

- directional transmissions
- transmit power adjustable in discrete levels
- no malicious detectors
- objective: minimize potential interference

Cost:

$\sum_{i=1,h} \pi(r_i (2\pi/\theta_i)^{1/\alpha})^2(\theta_i/2\pi)\rho_i(\tau_i/\tau_{min})$

h: number of hops from source to destination

r_i: omnidirectional interference range for hop i

α: pathloss exponent

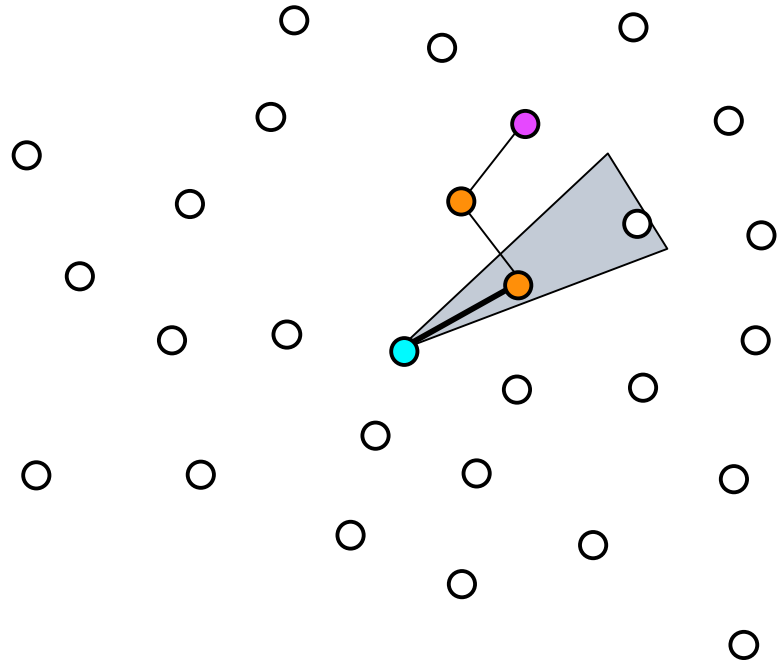
θ_i: beam width for hop i

ρ_i: expected density of nodes around hop i

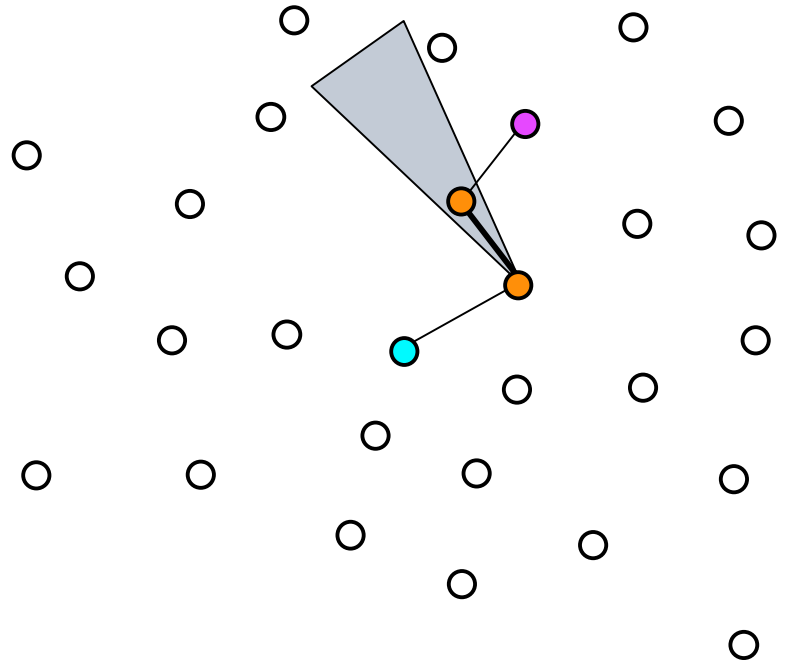
τ_i: expected air time for packet over hop i

τ_{min}: minimum expected air time over all hops considered

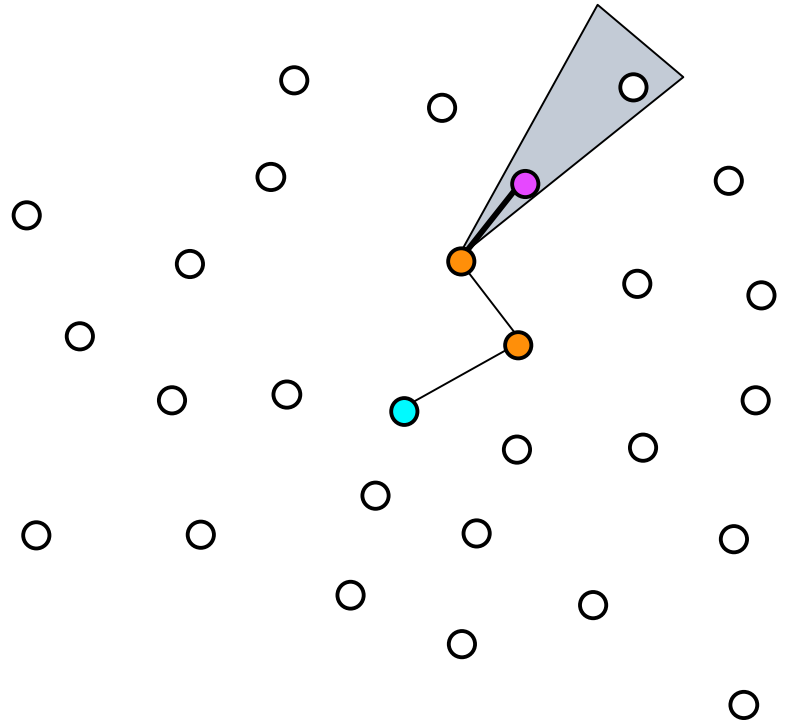
Low-Power Transmission



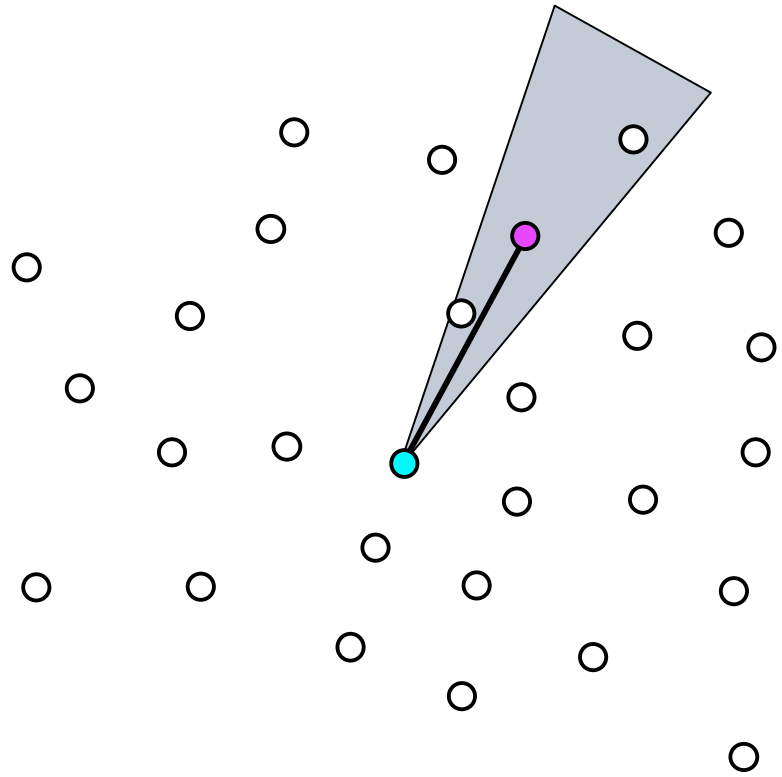
Low-Power Transmission



Low-Power Transmission



High-Power Transmission



Example 3

Assumptions:

- omnidirectional transmissions
- transmit power adjustable in discrete levels
- malicious detectors require few samples
- objective: minimize probability of detection

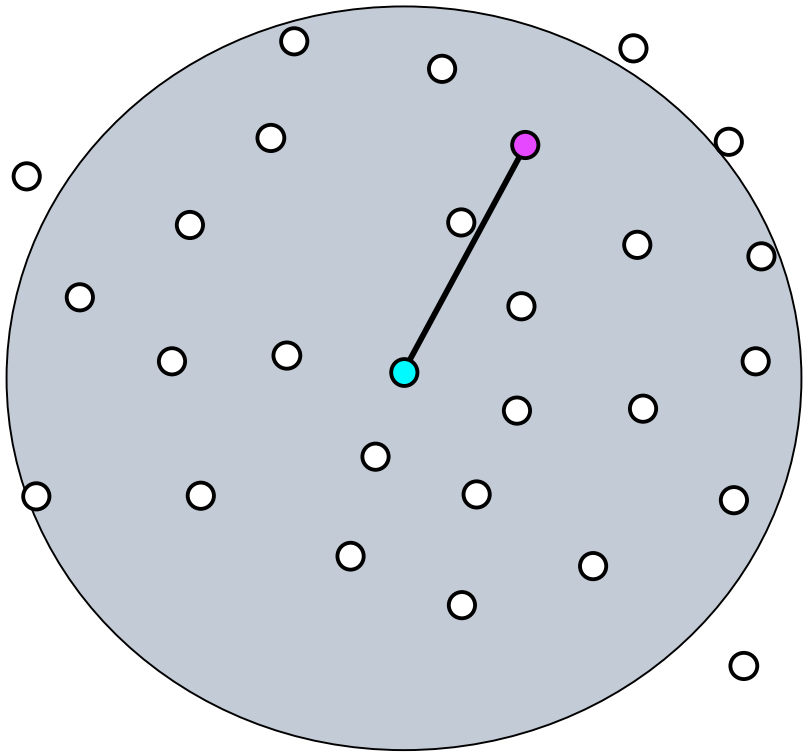
Cost:

$\sum_{i=1,h} \pi r_i^2$

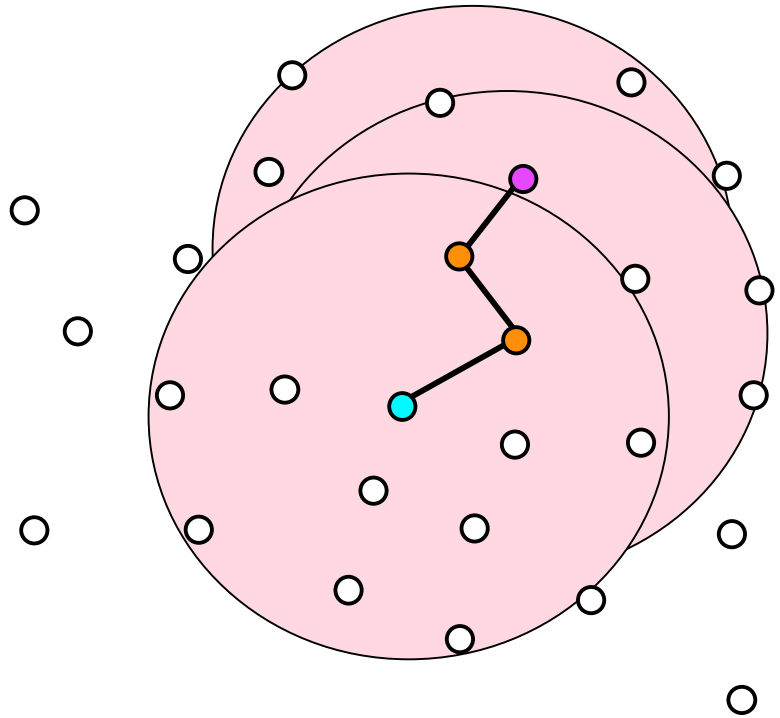
h: number of hops from source to destination

r_i: omnidirectional interference range for hop i

High-Power Transmission



Low-Power Transmissions



Summary

Topology control:

- network design and on demand
- uses information from both physical and application layers
- explicit interactions with other layers increases probability of meeting objectives
- knowledge of behavior of link layer (medium access) is critical for efficiency
- algorithms depend on communications context